STUDIES OF EXTRAGALACTIC NEBULAE

II. PRELIMINARY OBSERVATIONS OF THE ROTATION CURVE OF NGC 3310*

MERLE F. WALKER AND GUIDO CHINCARINI†
Lick Observatory, University of California, Mount Hamilton, California
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ABSTRACT

Spectrograms of NGC 3310 in position angles 0° and 90° have been measured for radial velocity out to about 25″ from the center. The largest velocity amplitude occurs in P.A. = 0°. It is not clear on the basis of only the two plates available whether the velocity slope observed in P.A. = 90° results from the orientation of the line of nodes or from some type of non-circular motion. Preliminary values of the mass, density, and mass-to-light ratio have been computed on the assumption that the line of nodes lies in P.A. = 0°. A unique feature of this galaxy is that the center of rotation does not coincide with the nucleus of the galaxy.

I. INTRODUCTION

NGC 3310 is, according to Humason, Mayall, and Sandage (1956), a galaxy of type Sb, with weak and shallow absorption lines, a spectral type of A8, and the observed radial velocities of +998 and 1039 km/sec. It was included in the program of spectroscopic observations of galaxies described in a previous paper (Chincarini and Walker 1967) because Duflot (1967) had found evidence of structure in the emission lines similar to that found in NGC 1068. As will be discussed in the following sections, the present observations are not adequate for the definitive determination of the motions in NGC 3310. However, we have felt that these observations are of sufficient interest in themselves to merit publication at this time.

II. OBSERVATIONS

NGC 3310 is described in the *New General Catalogue* as being "considerably bright, pretty large, round, very gradually, very suddenly much brighter nucleus 15″." Apart from the references given in § I, no modern investigations appear to have been made of this system. Direct photographs of NGC 3310 taken with the 120-inch reflector on Kodak 103aO plates and through a Schott GG 13 filter (2-mm thickness) are reproduced in Figures 1 and 2. The Ross corrector was not used for these observations. In Figure 1, exposure times from 5 sec to 10 min were used to bring out the structure of the galaxy all the way from the nuclear region out to the faint extremities of the system. All of the exposures, except for the 10-min one, were made on a single plate, moving the plateholder between exposures. Some spurious star images are thus superimposed on the various photographs.

Figure 1 shows that NGC 3310 has a bright nucleus, about $2\frac{1}{4}''$ in diameter, surrounded by two well-developed spiral arms whose major axis lies about in P.A. = 45°. Further out, many fainter arms appear with numerous condensations in them, characteristic of galaxies of type Sb. On exposures of intermediate length (40 sec and 1 min), the outline of the system appears nearly circular, while on the 10-min exposure the outline becomes elliptical again, this time with the major axis close to P.A. = 0°. As will be discussed later, it is not certain from the present observations whether these differences result simply from irregularities in the spiral structure of the galaxy, or whether

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† On leave 1964–1965 from Osservatorio Astrofisico, Asiago, Italy.

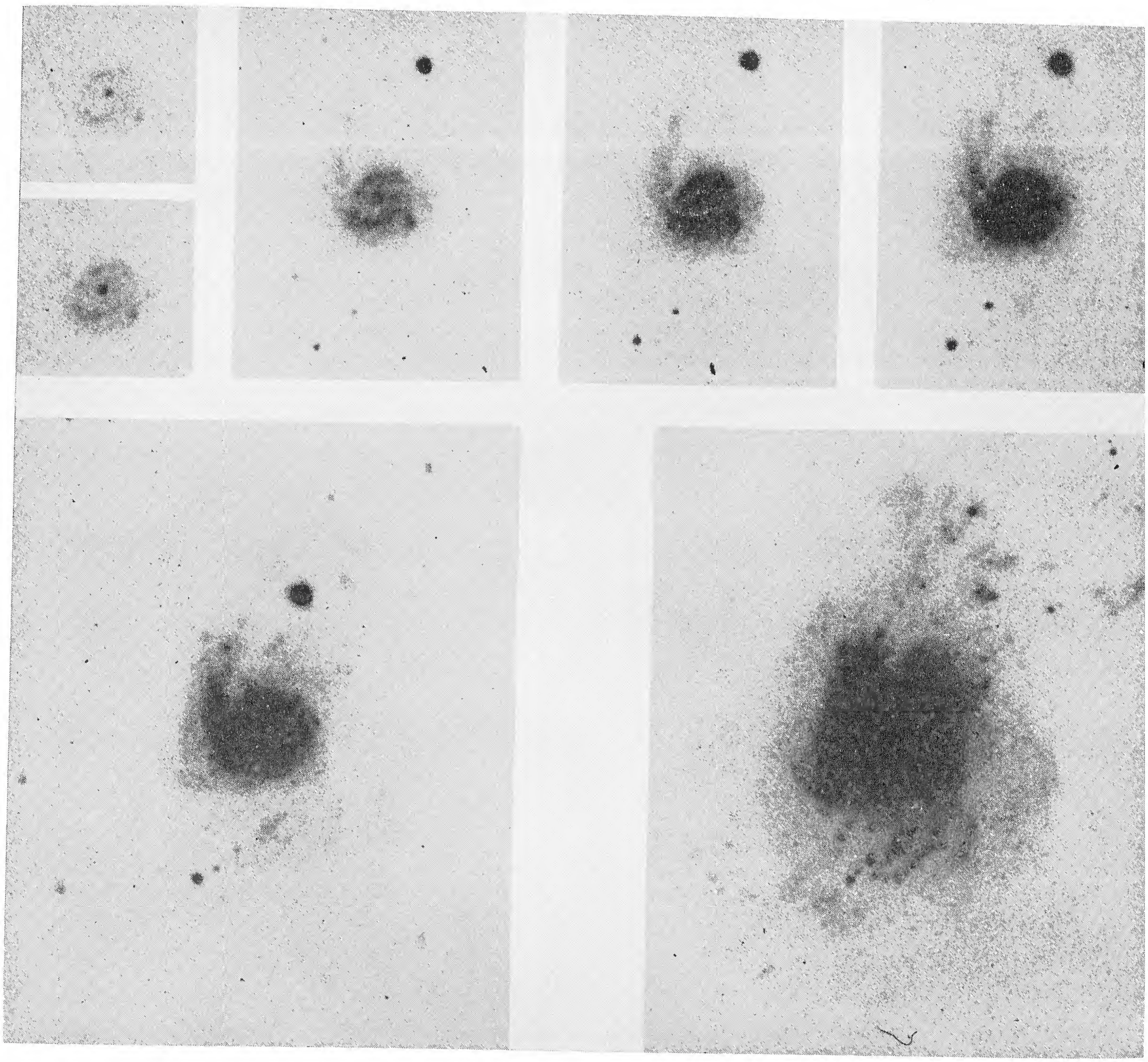

FIG. 1.—NGC 3310 photographed with the 120-inch reflector on Kodak 103aO plates and through 2 mm of Schott GG 13. Exposure times: 5, 10, 20, and 40 sec, 1, 2, and 10 min. All except the 10-min exposure were photographed on one plate. North is at the top, east to the left. The scale is 2.1″/mm.

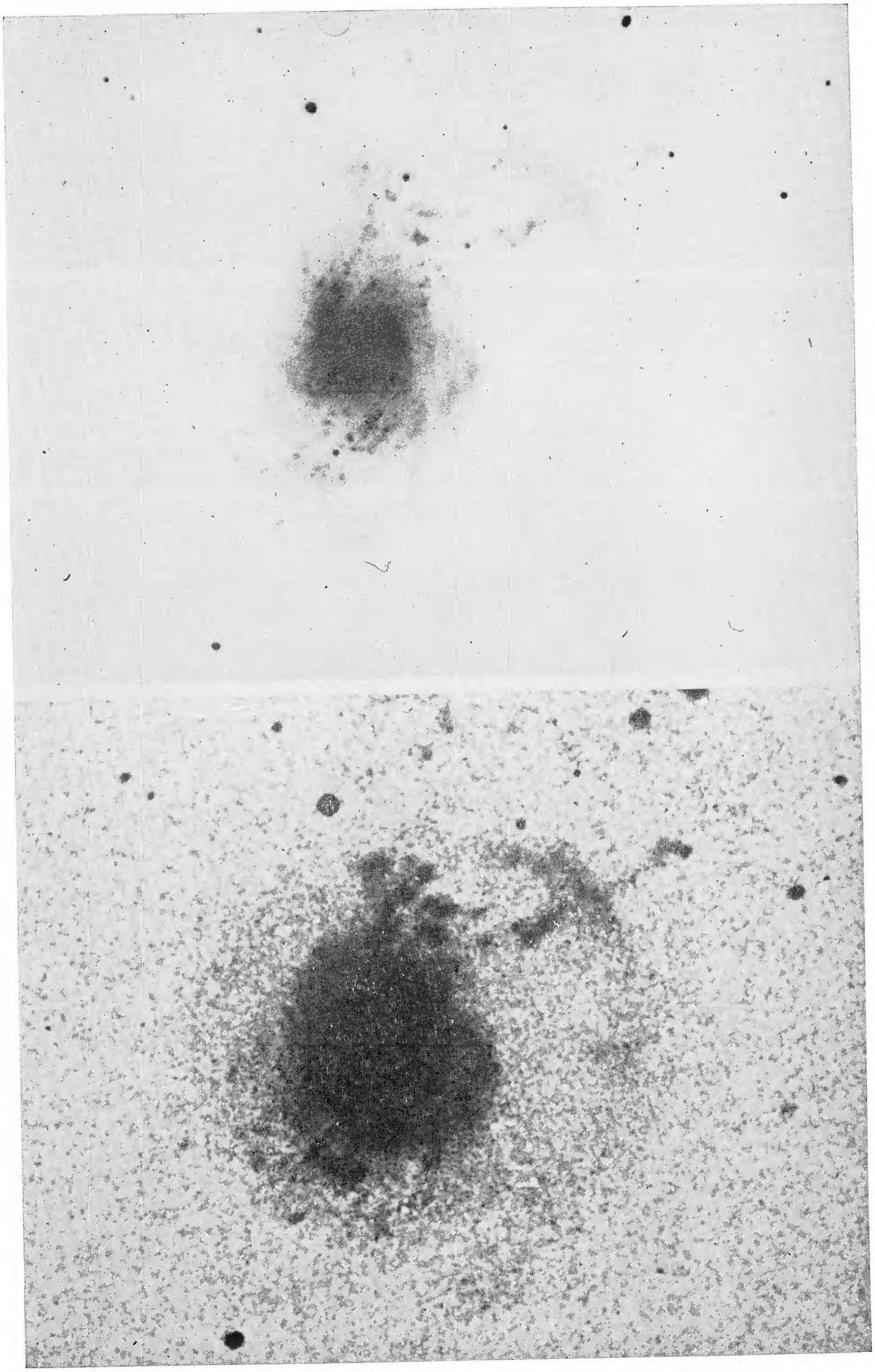

FIG. 2.—NGC 3310 photographed in blue light. *Top*, 10-min exposure with the 120-inch reflector. *Bottom*, reproduction of *National Geographic–Palomar Sky Survey* photograph and enlarged to the same scale. North is at the top, east to the left. The scale is 2.7″/mm.

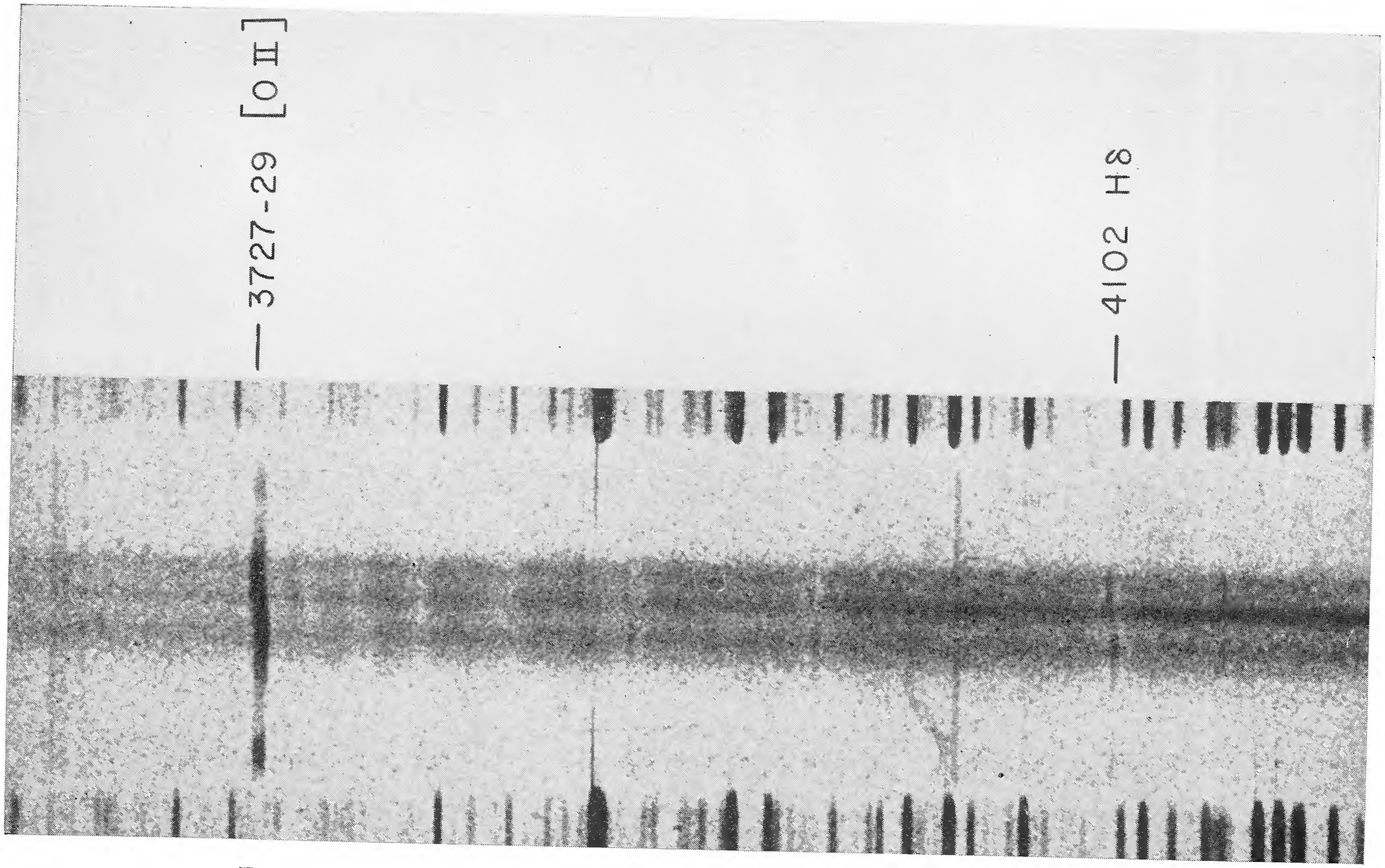

FIG. 3.—Spectrum of NGC 3310 in P.A. = 0°. North is at the top. The slit length is 60″

they might represent differences in orientation, and perhaps motion, of different parts of NGC 3310.

In Figure 2, the 10-min exposure with the 120-inch is reproduced again together with an enlargement to the same scale of the blue-light image of NGC 3310 on a plate of the *National Geographic–Palomar Sky Survey*. The scale of both pictures is smaller than of those in Figure 1, so that the outlying portions of the galaxy can be seen. Note the interesting "bow-and-arrow" structure in the northwest quadrant. This is produced by the brighter segment of the strong arm which can be traced all the way from the nucleus out to beyond this feature, and a jetlike feature extending outward from the central region of the galaxy. The nature of this latter feature is not clear. It could be merely a chance assemblage of condensations in faint spiral arms. However, the Palomar plate appears to show a continuous filament connecting the knots at the ends of the jet on either side of the "bow." Projecting the jet back into the central region of the galaxy, it is found that the projected line passes about 3″ north of the semistellar nucleus. It is not presently clear whether a discrepancy of this size rules out the possibility that the material has been ejected from the nucleus. To be sure of the nature of this feature, spectroscopic observations of it would be required; these will clearly be difficult to obtain owing to the low surface brightness of the feature.

As discussed above, both the amount and the position angle of the ellipticity of NGC 3310 change with distance from the center of the galaxy. Thus, the determination of the inclination of the galaxy to the line of sight is somewhat uncertain. Tentatively, until additional observations are obtained, we have chosen to determine the inclination from measures of the burned-out central portion of the image of NGC 3310 on the Palomar photograph reproduced in Figure 2. These measures give $b/a = 0.70$, corresponding to an angle between the normal to the equatorial plane of the galaxy and the line of sight of $i = 45^{\circ}.6$.

So far two spectra of NGC 3310 have been obtained, using the prime-focus spectrograph of the 120-inch reflector and a grating giving a dispersion of 96 Å/mm. The observations were made on baked Kodak IIaO film and cover the wavelength range from Hβ to about 3300 Å. Plate ES-438 is an exposure of 110 min on April 29, 1963 (U.T.), with the slit in P.A. = 0° along the apparent major axis of the outer spiral; an enlarged section of this spectrogram is reproduced in Figure 3. Plate ES-461 is a 180-min exposure on May 27, 1963 (U.T.), with the slit in P.A. = 90°. The plates were measured in a two-coordinate measuring engine, with the cross-wires turned to intersect the spectrum at an angle of 45° to the direction of dispersion. The appearance of the spectrum agrees in general with that given by Humason *et al.* (1956): it is of fairly early type, the only absorption lines visible being the hydrogen series and Ca II K. Narrow emission lines appear at $\lambda\lambda$3726–3729 [O II] (this doublet is partially resolved on the plates—slightly more so in P.A. = 0°—but not sufficiently to permit measurement of the two components separately), λ3638 [Ne III], λ4959 [O III], λ5007 [O III], and the Balmer series from Hβ through H13. There is no trace of structure in the emission lines of the sort observed in NGC 1068 (Walker 1963; Burbidge, Burbidge, and Prendergast 1959*a*). It has not been possible to measure the absorption lines since they are rather broad and, except for the K-line, have narrow emission components within them. It should be noted that the K-line appears double on these plates. One component agrees with the velocity of NGC 3310, while the other has no redshift and presumably must originate from interstellar absorption in our own Galaxy, although the width of this component is essentially the same as of that originating in NGC 3310.

The measurements of the narrow emission lines, reduced only to the Sun, are given in Table 1 and are shown graphically in Figures 4 and 5. In the table positive signs indicate distances north (P.A. = 0°) or east (P.A. = 90°) of the semistellar nucleus, while negative signs indicate distances south or west. Figure 4 shows that the velocity curve has a steep slope near the nucleus, a maximum at a radial distance of about

$r = 6''$ or $7''$, then decreases to $r = 15''$, after which it remains approximately constant. The abscissae in Figures 4 and 5 are measured from the semistellar nucleus. Measurement of the photographs in Figure 1 shows that the maxima of the velocity curve occur just at the points where the slit crossed the bright inner arms. The curve in Figure 4 represents the tentative rotation curve derived in the following section and projected onto the plane of the sky. This curve shows (1) that the rotation curve in P.A. = 0° is symmetric and (2) that the point of symmetry does not, as can be seen directly in Figure 3, coincide with the semistellar nucleus. Measurement of Figure 1 shows that this nucleus is, in fact, displaced from the center of the ellipse formed by the inner-arm system; in P.A. = 0°, the nucleus is displaced 0''.9 to the north of the center of the inner-arm system. The average velocity given by the curve in Figure 4 is +986 km/sec, with an uncertainty of perhaps ±5 km/sec. The intersection of this point with the curve comes at $r = 0''.8$ south, in good agreement with the observed displacement of the nucleus in Figure 1. Thus, the galaxy is seen to be rotating about the center of the inner-arm system while the semistellar nucleus (which is seen in Figure 1 to have a greater surface brightness than any other feature in the galaxy) is displaced from the center of rotation.

At the present time, the only method available for estimating the distance of the

TABLE 1

RADIAL VELOCITIES IN NGC 3310 AS A FUNCTION OF DISTANCE FROM CENTER IN PLANE OF SKY

r (sec of arc)	V_r (km/sec)	Lines Measured*
ES-438		
+20 0	956	1
+18 0	956	1
+16 0	956	1
+14 0	980	1
+12 0	987	1
+10 0	941	1
+ 8 0	901	1
+ 8 0	880	2
+ 6 0	885	1
+ 6 0	890	2
+ 4 0	909	1
+ 4 0	910	2
+ 2 0	925	1
+ 2 0	922	2
0 0	980	1
0 0	948	2
− 2 0	1058	1
− 2 0	1038	2
− 4 0	1074	1
− 4 0	1073	2
− 6 0	1097	1
− 6 0	1076	2
− 8 0	1081	1
− 8 0	1080	2
−10 0	1074	1
−10 0	1093	2
ES-438		
−12 0	1066	1
−12 0	1069	2
−14 0	1050	1
−16 0	1043	1
−18 0	1018	1
−20 0	1018	1
−22 0	1018	1
−24 0	1018	1
−26 0	1035	1
−28 0	1035	1
−30 0	1043	1
ES-461		
+21 0	950	1
+19 0	980	1
+17 0	965	1
+15 0	952	1
+13 0	928	1
+13 0	945	2
+11 0	952	1
+11 0	924	2
+ 9 0	980	1
+ 9 0	953	2
ES-461		
+ 7 0	980	1
+ 7 0	964	2
+ 5 0	975	1
+ 5 0	975	2
+ 3 0	975	1
+ 3 0	965	2
+ 1 0	975	1
+ 1 0	986	2
− 1 0	991	1
− 1 0	971	2
− 3 0	960	1
− 3 0	965	2
− 5 0	991	1
− 5 0	977	2
− 7 0	1006	1
− 7 0	986	2
− 9 0	1022	1
− 9 0	1014	2
−11 0	1030	1
−11 0	1018	2
−13 0	1038	1
−13 0	1020	2
−15 0	1014	1
−17 0	1030	1
−19 0	999	1

* Lines measured:
1 Average of em λλ3726–3729 [O II].
2 Average of em λ3869 [Ne III], λ3889 H8, λ3970 Hε, λ4102 Hδ, and λ4861 Hβ

galaxy is by use of the redshift. Taking the value of the redshift given above, correcting for solar motion using the formula given by Humason *et al.* (1956) and using $H = 98$ km/sec/10^6 pc (Sandage 1961), the distance of NGC 3310 becomes 1.1×10^7 pc. Since the redshift is small, the uncertainty in the distance determined in this way is clearly appreciable and could easily amount to 20 or 30 per cent. With this value of the distance, the displacement of the nucleus from the center of rotation is 43 pc while the diameter of the nucleus is about 120 pc.

Figure 5 shows that an appreciable velocity slope occurs along the supposed minor axis of NGC 3310. From only two plates it is not possible to determine uniquely whether

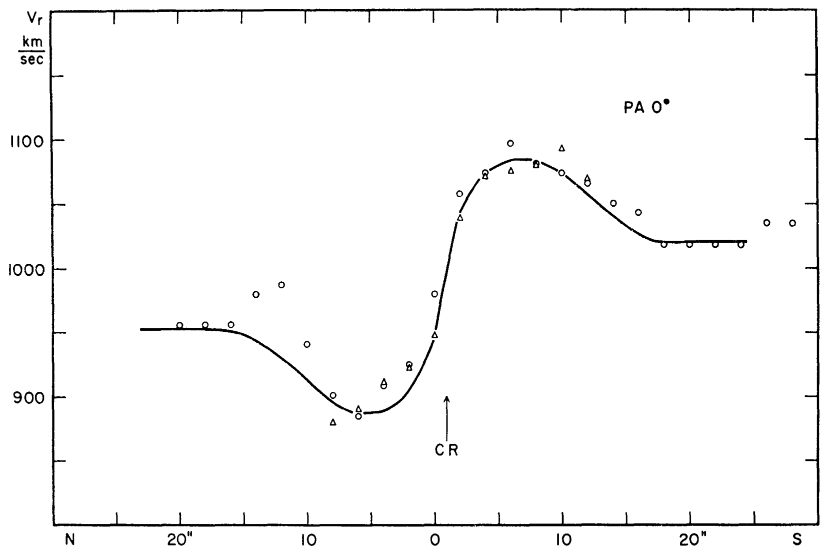

FIG. 4.—Velocity curve of NGC 3310 in P A. = 0°. Ordinate is radial velocity in the plane of the sky reduced to the Sun; abscissa is distance from the semistellar nucleus. The circles represent measurements of em. [O II] λλ3726–3729, triangles represent the average of all other emission lines measured except λλ3726–3729 The curve represents the theoretical rotation curve calculated for the four-similar-spheroid model Note that the center of rotation (CR) does not coincide with the nucleus of the galaxy.

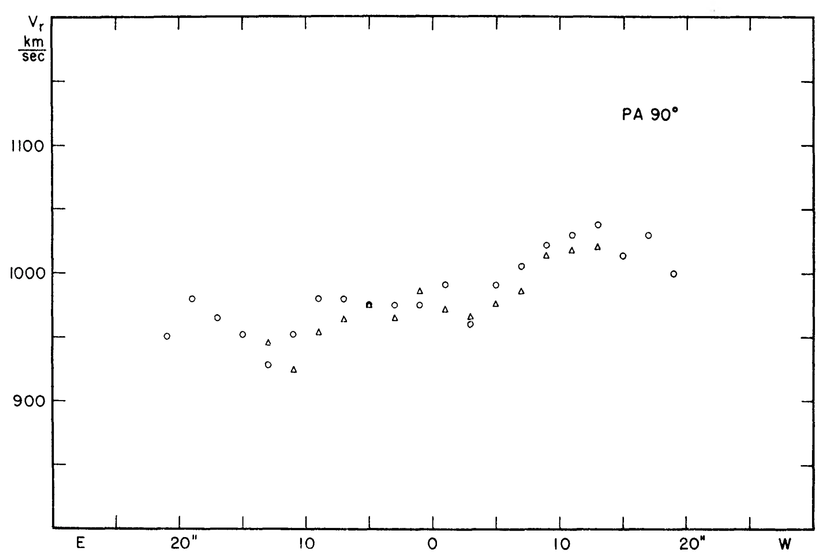

FIG 5 —Velocity curve of NGC 3310 in P.A. = 90°. Ordinate, abscissa, and symbols as in Fig 3 this slope results from the fact that the line of nodes lies in some other angle than P.A. = 0° or whether some type of non-circular motions occur. Furthermore, if we suppose that the slope results from not observing along the perpendicular to the line of nodes, the determination of the position angle of the line of nodes depends very much upon what portion of the velocity curve is used to calculate that angle. If we use the portion of the velocity curve in Figure 4 for $r < 8''$, we find that the position angle of the line of nodes is about $\Phi = 3°$, while if we use the portion between $20'' < r < 30''$, we find that the line of nodes should lie more nearly in position angle 45°; it will be recalled (§ II) that this is the P.A. of the major axis of the inner-arm region. This comes about because the velocity curve in P.A. = 90° does not reflect the shape of the curve in P.A. = 0°; instead of having a maximum slope near the nucleus, as does the curve in P.A. = 0°, the curve at 90° is rather flat near the nucleus and tends to increase its slope for $r > 5''$. The effects are not very much larger than the errors of measurement, but such a difference, if real, could indicate that at least part of the slope at 90° results from non-circular motions.

III. PRELIMINARY MASS DETERMINATIONS

Owing to the uncertainties discussed above, it is not possible without additional spectroscopic observations in different position angles to derive a definitive rotation curve for NGC 3310 or to determine whether only circular motions exist. It is planned to obtain such observations in the future. We have, however, calculated a preliminary rotation curve by supposing that the line of nodes is $\Phi = 0°$, and neglecting the effect of any possible non-circular motions. By use of the inclination factor from § II, three different mass determinations have been made: (1) For $r \leq 5''$, the velocity curve has been approximated by a straight line and the mass determined on the basis of solid-body rotation. This procedure gives $\mathfrak{M} = 1.2 \times 10^9 \mathfrak{M}_\odot$, and an average density of $\bar{\rho} = 1.0 \times 10^{-21}$ gm cm^{-3}, assuming a spherical model. (2) For the same radius, the mass has been determined using the single-ellipsoid model of Burbidge *et al.* (1959*a*), with a ratio of axes of $c/a = 0.1$. This model gives $\mathfrak{M} = 5.2 \times 10^8 \mathfrak{M}_\odot$, and an average density of $\bar{\rho} = 4.5 \times 10^{-21}$ gm cm^{-3}. (3) Out to $r = 25''$, the mass has been determined using a model, developed by Burbidge *et al.* (1959*b*), in which the surfaces of equal density are similar spheroids. In this solution, the observed velocity curve was represented by a polynomial of the form

$$\frac{V_r}{r} = \sum_{n=0}^{n=4} b_n r^n ,$$

where V_r is the observed radial velocity. The resulting theoretical rotation curve, in the plane of the sky, is shown by the curve in Figure 4. Taking $c/a = 0.1$ and $i = 45\overset{\circ}{.}6$, this solution leads to a central density of $\rho_0 = 3.0 \times 10^{-20}$ gm cm^{-3} and the variation of density with radial distance shown in Figure 6. The mass out to $r = 25''$ is found to be $\mathfrak{M} = 1.4 \times 10^{10} \mathfrak{M}_\odot$. No correction for the so-called pressure term has been made since the shape of the velocity and density curves indicate that none is needed.

IV. MASS-TO-LIGHT RATIO

Derivation of the final value of the mass-to-light ratio must await the definitive determination of the distance and mass of NGC 3310. However, the necessary photoelectric measurements of the brightness and color of this galaxy with different focal plane diaphragm sizes have been made, using the 24-inch photoelectric telescope. The observations were made using a refrigerated 1P21 photomultiplier cell and the following filters: V = Corning 3384, standard optical thickness; B = 1-mm Schott BG 12 plus 2-mm Schott GG 13; UV = Corning 9863, standard optical thickness. The measurements were reduced to the UBV system of Johnson and Morgan (1953) by comparison with standard stars of that system. Circular diaphragms were used throughout. The observations are listed in Table 2.

The following tentative values of the mass-to-(blue)-light ratio, in solar units, have been derived by the method described in Paper I (Chincarini and Walker 1967), which corrects the observed photoelectric measures to a given radius for light from exterior portions of the galaxy included in the line of sight through the photometer diaphragm. From the photoelectric measures, the surface brightness of the galaxy in magnitudes per square second as a function of distance from the center was calculated, and the results are listed in Table 3. From this table a curve of the brightness in intensity units was constructed, and it was assumed that the surface brightness is zero at $r = 60''$. The intensities were multiplied by $b/a = 0.70$ to correct them approximately for the fact that they were observed through circular diaphragms; it was found in Paper I that the correction for the effect of using circular diaphragms in NGC 4736 is approximately equal to b/a, and in NGC 3310 we can, in the absence of other data, only assume that the correction would in this case also be equal to b/a. The luminosity distribution was then approximated by a model consisting of twenty-one similar spheroids, having a ratio of axes $c/a = 0.1$. The integral luminosity was then calculated out to the desired radius by add-

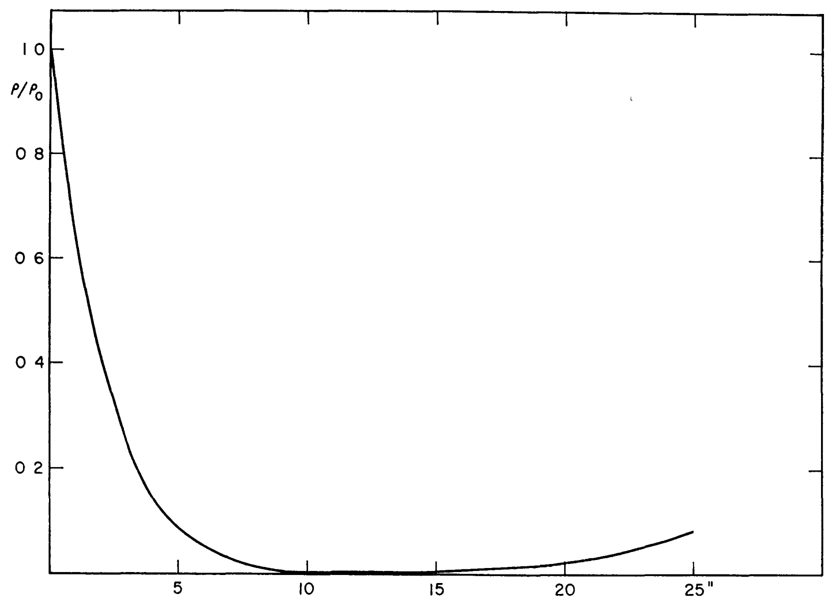

FIG. 6.—Variation of density with radial distance in NGC 3310 calculated from the four-similar-spheroid model. The ordinate is in units of the central density which is $\rho_0 = 3.0 \times 10^{-20}$ gm cm^{-3}.

TABLE 2

PHOTOELECTRIC OBSERVATIONS OF NGC 3310*

Diaphragm Diameter	V	$B-V$	$U-B$	No. Obs
11″	12 88	+0 29	−0.54	4
17″	12 14	28	54	3
28″	11 50	.28	52	1
59″	11 06	28	58	1
128″	10 84	+0 29	−0 48	1

* Measurements referred to the sky, 1° north

ing the luminosities of the individual spheroids out to that radius. These luminosities were combined with the values of the mass obtained in the preceding section to give the values of the mass-to-light ratio listed in the second column of Table 4. For comparison, the third column lists the values of the mass-to-light ratio obtained by simply interpolating the observed magnitudes in Table 2 for the appropriate radial distance from the center, without correction for the fact that circular diaphragms were used or for the inclusion of light from exterior parts of the galaxy. No correction has been made for galactic absorption or for absorption in NGC 3310.

The mass-to-light ratios found using the corrected values of the intensity are somewhat larger than those found in NGC 4736 (Paper I) and smaller than usually supposed for a galaxy of type Sb (de Vaucouleurs 1959). It must be emphasized, however, that

TABLE 3

SURFACE BRIGHTNESS OF NGC 3310

r (sec of arc)	B Mag per Square Sec of Arc	r (sec of arc)	B Mag per Square Sec of Arc
2 8	17 93	21 8	20 84
7 0	18 49	46 8	23 00
11 0	19 13		

TABLE 4

MASS-TO-LIGHT RATIO (BLUE LIGHT)

r (sec of arc)	M/L	
	Using Corrected Magnitudes	Using Observed Magnitudes
5	2 4	1 0
25	5 9	1 6

these results are uncertain owing to uncertainties in the position of the line of nodes, the inclination, the distance, and the fact that the photometry does not extend to large distances from the center of NGC 3310.

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